CENTER FOR SPACE POLICY AND STRATEGY

APRIL 2018

THE POLICY AND SCIENCE OF ROCKET EMISSIONS

MARTIN ROSS AND JAMES A. VEDDA
THE AEROSPACE CORPORATION

IMAGE COURTESY ULA

MARTIN ROSS

Dr. Martin Ross is senior project engineer for commercial launch projects. In that capacity, he leads research concerning the effects of space systems on the stratosphere—mainly, the impact of rocket-engine emissions on stratospheric ozone and climate forcing. He is developing new interagency strategies to better understand the scientific, economic, and policy implications of these phenomena. Ross conceived and implemented the Rockets Impacts on Stratospheric Ozone (RISO) program for the Air Force, managing simultaneous airborne sampling and ground-based remote sensing of rocket plumes. He also served as mission scientist for the joint NASA/NOAA/Air Force Atmospheric Chemistry of Combustion Emissions Near the Tropopause (ACCENT) project and is a contributor to the World Meteorological Organization's Quadrennial Scientific Assessment of Ozone Depletion reports. He has written more than 50 publications and holds a Ph.D. in planetary and space physics from UCLA.

JAMES VEDDA

Dr. James A. Vedda is senior policy analyst in the Center for Space Policy and Strategy. In this role, he performs analyses on national security, civil, and commercial space issues for NASA, the Federal Aviation Administration, the Department of Commerce, the Air Force, and the National Geospatial-Intelligence Agency. Vedda is the author of two books: *Choice, Not Fate: Shaping a Sustainable Future in the Space Age* (2009), and *Becoming Spacefarers: Rescuing America's Space Program* (2012). He holds an M.A. in science, technology, and public policy from George Washington University and a Ph.D. in political science from the University of Florida.

ABOUT THE CENTER FOR SPACE POLICY AND STRATEGY

The Center for Space Policy and Strategy is dedicated to shaping the future by providing nonpartisan research and strategic analysis to decisionmakers. The Center is part of The Aerospace Corporation, a nonprofit organization that advises the government on complex space enterprise and systems engineering problems.

Contact us at www.aerospace.org/policy or policy@aero.org

Abstract

Combustion emissions from rocket engines affect the global atmosphere. Historically, these impacts have been seen as small and so have escaped regulatory attention. Space launch is evolving rapidly however, characterized by anticipated growth in the frequency of launches, larger rockets, and employment of a greater variety of propellants. At some future increased launch rate, the global impacts from launch emissions will collide with international imperatives to manage the global atmosphere. This could result in regulation of launch activity. The regulatory uncertainty is complicated by knowledge gaps regarding rocket emission impacts. Looking ahead to the coming decade, the global launch industry and its stakeholders should encourage, facilitate, and fund objective scientific research on rocket emissions and engagement with international regulators to define metrics. Such a policy would forestall unwarranted regulation, ensure regulatory impartiality across the global launcher fleet where regulation is unavoidable, and facilitate launch industry freedom of action in crafting responses to environmental concerns.

Fool Me Twice, Shame on Me

Concerns about atmospheric rocket emissions are analogous to early recognition of space debris, which continues to be a policy challenge today. Debris accumulation in valuable orbits is widely acknowledged to present an existential risk to continuing space operations and industry growth.[1] Nevertheless, policy and practice to decisively deal with the problem are still in the formative stages, even as technology to reduce the risk via active disposal is on the horizon. If the potential magnitude of the space debris problem had been recognized early in the space age, and coordinated international actions had been taken at the time to address it, space debris may not have become the significant risk we face today.

With hindsight, we can appreciate the formidable technical, geopolitical, and national security obstacles that prevented early resolution of the problem. Regardless of the cause of early inaction, space debris was not addressed and the situation evolved into a classic example of "the tragedy of the commons." Half a century ago a potential problem presented itself, but a lack of urgency prevented good policy from being established when the problem was in its nascent stage. The result is that some regions of Earth's orbital space present hazardous conditions due to debris accumulation.

Today, launch vehicle emissions present a distinctive echo of the space debris problem. Rocket engine exhaust emitted into the stratosphere during ascent to orbit adversely impacts the global atmosphere. Rocket exhaust has two main effects on the atmosphere. First, chemical reactions deplete the ozone layer.[2] This has, historically, been the main concern about rocket emissions because solid rocket motors inject chlorine directly into the ozone layer and chlorine has been subject to international regulation since 1987.[3] More recently, a second concern has come to light.[4] Particles injected into the stratosphere absorb and reflect solar energy, changing the flow of radiation in the atmosphere, heating the stratosphere and cooling the surface, respectively. This radiative forcing has the effect of changing the Earth's albedo and so the amount of solar energy injected into the atmosphere. These thermal changes also deplete the ozone layer.[5]

Rocket emissions have never been a priority for the scientific community. The literature is sparse and the present state of understanding of rocket emissions is weak. New fuels such as methane, about which no research has been done and which is a strong absorber of infrared radiation, will soon see wide use,[6] further reducing the accuracy of estimates. Nevertheless, the meager amount of available research permits an assumption that present day ozone depletion and radiative forcing caused by launch emissions are likely small components of the sum of human influences on the atmosphere.

Although rocket impacts to the global atmosphere are presently insignificant compared to other human activities,[7] trends that include plans for airline-like operations, massive LEO communication satellite constellations, and space tourism indicate rocket impacts are likely to grow, possibly to the point of being considered significant. By most estimates and analyses from space planners, the pace and dimension of launches, and therefore emissions, will increase in coming years.[8] The rate of orbital launches nearly doubled in the past decade, and may accelerate further. If we apply the lessons learned from space debris, now is the time to develop and implement policy to mitigate the risks to the natural and operational environments from rocket emissions.

Like orbital debris, atmospheric rocket emissions have the long-term potential for risk to undermine efficient, routine space system operations if left to grow without attention. Regulation of launch vehicle emissions will not happen at current launch rates, but a confrontation between launch operations and international efforts to protect stratospheric ozone and manage atmospheric radiation is likely if the space industry expands as many space planners expect. This predicament was first pointed out in the context of the economics of launch vehicle reusability.[9] The timing of this "tipping point" will be determined by the aggressiveness of international regulators as they react to increasing launch rates and greater visibility of the space industry.

The next section briefly describes how rocket emissions affect the atmosphere and could attract the attention of regulators. This is followed by suggested actions to anticipate and mitigate this risk.

Launch Vehicle Emissions and the Global Atmosphere

Launch vehicle emissions disturb the atmosphere.[4,10] Emissions into the troposphere (the layer nearest to the ground) are not important, aside from transient launch and landing site air quality concerns that local authorities already deal with. Emissions into the stratosphere are very different. The stratosphere is dynamically isolated from the troposphere beneath so that emissions in this layer can accumulate. Also, it contains the ozone layer so that the stratosphere has been the focus of strong international regulation since 1987 through the Montreal Protocol on Substances That Deplete the Ozone Layer.[3]

The stratosphere is a particularly sensitive region into which rockets directly inject combustion products—gases and particles—that will have impacts prompting the attention of policy-makers. The first suggestion that rocket emissions should be regulated appeared in 1994.[11] The primary perturbations to the atmosphere from rocket emissions are stratospheric ozone depletion and a change in the atmosphere's net radiative balance, a radiative forcing, that results in temperature changes throughout the atmosphere. Secondary changes include changes in the pattern of global circulation and cloudiness, including polar mesospheric clouds.[12]

While the magnitude and variety of rocket emission impacts are not well known, we can describe the overall picture across the various propellant combinations with some confidence. CO_2 and H_2O emissions, which make up the main portion of all rocket exhaust, are unimportant, even at launch rates orders of magnitude greater than today. This is a key aspect of rocket emissions. Research has shown that a fleet of hydrogen-fueled launch vehicles, whose emissions are nearly

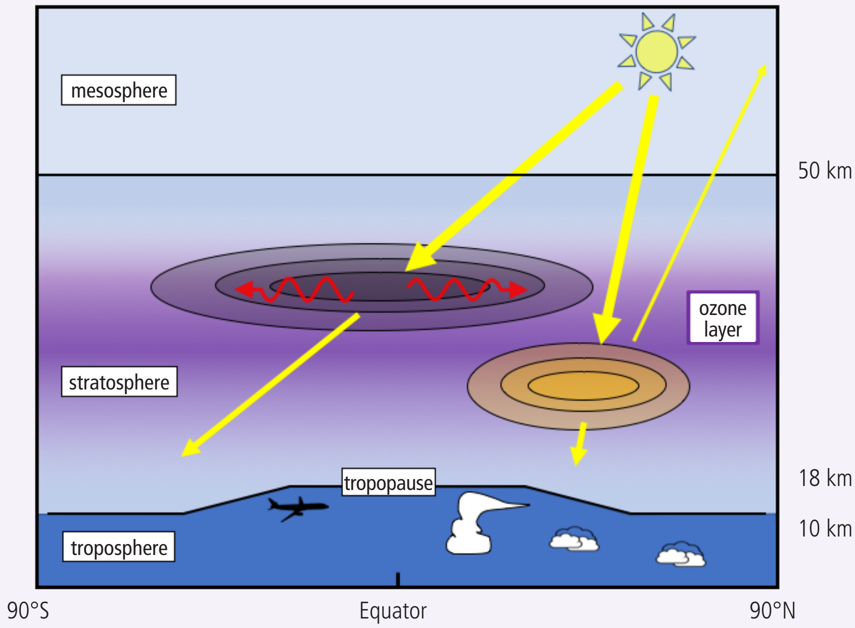
Earth's Atmosphere with Rocket Engine Particulate Accumulations

The lowest region of Earth's atmosphere—the troposphere—is largely decoupled from the stratosphere above it. The rate of air mass exchange across the tropopause is slow; a small particle injected into the stratosphere, from large volcanic eruptions for example, may remain in the stratosphere for several years. Eventually, stratospheric particles flow downward across the tropopause, ultimately reaching the surface, typically by precipitation.

This phenomenology means that particles emitted into the stratosphere by the most recent three to four years of rocket launches accumulate there. The black carbon (BC, or soot) particles (mainly from kerosene-fueled engines) accumulate in the upper stratosphere (30–50 km) and are carried by atmospheric circulation into both hemispheres. The larger and heavier alumina particles (from solid rocket motors) tend to remain in the northern hemisphere (where most launch sites are located) and in the lower stratosphere (20–30 km). Critically, both particle accumulation layers reside at altitudes that include the Earth's protective ozone layer.

The BC layer particles act as a thin "black umbrella" that intercepts a small fraction of sunlight, transferring the intercepted energy to, and so warming, the surrounding stratosphere. The "black umbrella" thus slightly cools the Earth's surface. The alumina layer particles act as a thin "white umbrella" that reflects sunlight back to space, further cooling the Earth's surface. Therefore, the particle "umbrellas" cool the Earth's surface at the expense of a warmer stratosphere. While individual particles from the alumina accumulation layer have been detected by aircraft in the lowermost stratosphere, the global BC and alumina accumulations have not been subject to focused observation and so are yet to be measured and characterized.

While cooling the surface may seem beneficial, the BC and alumina accumulation layers harm the ozone layer. They do this in two ways. First, a slightly warmer stratosphere accelerates existing chemical reactions that reduce ozone levels. Second, chemical reactions on the collective surface area of the alumina particles also reduce ozone. The net effect of the particles is poorly understood and it is not clear which of these processes dominates over the other. The most accurate estimate that can be made is that at present launch rates and propellant use, global ozone depletion from rocket engine particle emissions does not exceed 0.1% … a small but growing injury to the ozone layer struggling to recover from long banned chlorofluorocarbons.



entirely water vapor, could launch at any rate possible without risk of regulatory attention.[13] Rocket CO_2 and H_2O emissions are not of any concern with respect to atmospheric impacts.[4]

The important emissions of concern with respect to global impacts are chlorine and alumina particles from solid rocket motors (SRMs) and soot particles (hereafter, black carbon or BC), mainly, though not exclusively, from kerosene fueled engines. Chemical reactions involving chlorine and the surface of alumina particles cause ozone loss directly.[14] Alumina and BC particles accumulate in the stratosphere in distinct layers and intercept incoming solar radiation.[15] As the lifetime of small particles injected into the stratosphere is as long as four years, the steady state BC and alumina loading represents the contribution from all global launches during the past several years.

These alumina and BC layers reflect and absorb a small portion of the downward solar flux, respectively.[4,14] The energy from the intercepted solar flux warms the stratosphere, indirectly adding to ozone loss by accelerating ambient ozone-destroying reactions. Importantly, solar flux is reduced beneath the alumina and BC layers which act as a sort of "stratospheric umbrella" producing a negative radiative forcing that cools the Earth's surface. Rocket emissions therefore act in the same manner as geoengineering schemes to counteract the warming from greenhouse gases. This equivalence may have policy implications.

Within this picture, the actual magnitudes of ozone loss and stratospheric heating (as well as surface cooling) from space launch are poorly known. Application of sophisticated global atmosphere models to the problem of rocket emissions have been sparse and incomplete. The few models employed to date have been narrowly focused on unimportant emissions (for example, water vapor), have not applied a consistent methodology, and have not incorporated the complete canonical picture described above.

The research done in the past two decades, while inadequate for detailed assessments, does allow for order-of-magnitude estimates for the ozone depletion and radiative forcing from the global launch fleet. Present-day global direct ozone loss from chlorine, reactive alumina surfaces, and from the BC accumulation is estimated to be greater than 0.01% and less than 0.1%.[7] For comparison, the global ozone loss from long banned ozone depleting substances (ODSs) is about 3%.[16] Clearly, if launch emissions were to increase by a factor of ten, the associated rocket ozone loss could be of an order comparable to ODS loss.

Estimating the net radiative forcing from absorption and scattering of solar energy by the BC and alumina stratospheric accumulations is difficult; we have only one model of a specific case to deduce a more general understanding.[14] We may use this paper, together with models of BC and alumina based geoengineering[5] to estimate that rocket BC and alumina global radiative forcing equals on the order of negative 10 milliwatts per square meter. It is important to note the sign of the radiative forcing: rocket emissions cool the Earth's surface. One model of future rocket BC emissions (larger than present day emission) predicts a surface cooling exceeding 1° C in a narrow latitude band directly beneath the BC accumulation.[14] For comparison, the radiative forcing from global greenhouse gas (GHG) emissions is about positive 3 watts per square meter,[17] several orders of magnitude greater than the estimated present day rocket forcing.

This cursory description of the current level of understanding of rocket emissions and their global impacts makes clear how little is known about rocket emissions impacts; the accuracy of knowledge is an order of magnitude at best. We can more concisely describe the situation using specific terminology developed by climate scientists to express the confidence about facts and understanding.[18] By this nomenclature, we have Low Confidence in the overall description of rocket impacts and Very Low Confidence in the numerical evaluation of present-day ozone depletion and radiative forcing.

The Current Policy Environment

What policies have addressed rocket emission impacts on the global atmosphere? Like space debris, the perceived "smallness" of the impacts and their unique character has left them in a policy void without consistent or directed attention. The following paragraphs briefly review these polices, with an eye towards anticipating and addressing future changes.

National policy towards rocket emissions began with the National Environmental Protection Act (NEPA),[19] established in 1974 to evaluate the impact of all new industrial activities. Under the NEPA process, any new

Federal activity must prepare an Environmental Impact Statement (EIS) that describes how the new system will affect the environment, including the atmosphere. Launch systems have gone through this process and many EIS documents have been assembled related to launch systems. The NEPA process does not formally have regulatory authority; it was developed mainly for informational purposes.

The information contained in EIS documents is largely disconnected from the scientific community and is not subject to peer review. Importantly, NEPA does not require new scientific research be done. Thus, EIS documentation can be misleading, inaccurate, and overlook important information. Also, NEPA regards each system independently and only includes systems with Unites States origination. NEPA's statutory requirements therefore provide little information on the global impact of rocket emissions.

On the international stage, orbital launches were historically considered a national security matter and therefore beyond the scope of environmental regulation. The scientific community accordingly paid no attention to rockets even as significant research was being done to understand hypothetical supersonic transports. The introduction of the Space Shuttle changed this situation as it became the single largest rocket emission source by orders of magnitude.

The Shuttle was too great of a stratospheric emission source to be ignored. The scientific community accordingly took policy cues from the Montreal Protocol to investigate SRM emissions. At first only SRM chlorine emissions were of interest. However, in 1997 laboratory experiments demonstrated how the surface of alumina particles emitted by SRMs can promote ozone-destroying chemical reactions.[20] Subsequent models that included these heterogeneous reactions showed that alumina particles could indirectly cause more ozone loss than chlorine would directly.

Based on questions expressed by the Montreal Protocol, the scientific community produced several models of the impact of Space Shuttle SRMs,[13] but ignored other propellants. Research included direct sampling of SRM plumes, which indicated the alumina surface effect might be larger than expected. The uncertain microphysics of emitted alumina became the focus of limited research.[21]

However, by the turn of the century the Space Shuttle was not launching at the rate originally predicted and the global launch rate had declined during the 1990s. Rockets appeared to be a small and declining emission source. The policy cues transmitted to the scientific community had changed; rocket emissions were no longer of regulatory interest. As a result, research interest in rocket emissions waned and since the turn of the century, little research has been done.

Focus on the Montreal Protocol is warranted because it is widely seen as the most successful international agreement of its kind and it directs, through various channels, research priorities. Despite changes in the political situations among the various party nations, the Montreal Protocol has remained a strong regulatory force since its inception in 1987. As evidence of its continuing strength, in 2017 the Montreal Protocol banned a class of compounds known as hydrofluorocarbons (HFCs).[22] HFCs were not banned because of ozone depletion (they originated as CFC replacements) but rather due to their predicted future radiative impact. This is an important point: the Montreal Protocol regulates based on radiative forcing as well as ozone depletion.

The Montreal Protocol does not specifically address emission sources such as rockets that emit directly into the stratosphere. . . .

The Montreal Protocol does not specifically address emission sources such as rockets (and aircraft) that emit directly into the stratosphere. Compounds are identified for global phase-out based on a calculated Ozone Depletion Potential (ODP), a metric that compares a compound's ozone depletion (per unit mass) to the ozone depletion caused by a standard compound. However, ODP is strictly defined only for gases released at the Earth's surface, so rocket emissions cannot formally be assigned an ODP for assessment. For rocket emissions, the assessment therefore regresses to subjective descriptions. The impacts of rocket emissions on stratospheric ozone are occasionally assessed in the Montreal Protocol's Quadrennial Scientific Assessment of Ozone as "small" without a clear definition of "small" (or "large") and without considering future launch rate growth.

Coupling vague assessments such as "small" with Low or Very Low Confidence scientific understanding of rocket emissions leads to a policy gap that presents a risk for space launch. That is to say, rocket emissions impacts are ill-understood and the regulatory metric is ill-defined. This policy gap appears at a time when the Montreal Protocol remains an influential and active multilateral instrument, phasing out compounds based on their impact to global ozone and to climate forcing. And while the Montreal Protocol has successfully saved the ozone layer from severe degradation, the problem of ozone depletion is not fully solved. Ozone levels are still declining in some stratospheric regions.[23] This suggests that the Montreal Protocol could be applied to poorly understood "small" impacts, such as launch emissions.

These uncertainties, the lack of understanding of rocket emissions, the lack of formal metrics, and the growing influence of the Montreal Protocol present a clear risk of sudden and unanticipated change in the status of rocket emissions with respect to international regulatory attention.

The launch industry has benefitted so far from this policy vacuum…

Finally, International Space Law, as promulgated through the Outer Space Treaty of 1967,[24] has nothing to say about the atmospheric emissions problem. Article IX relates to activities in space that would "cause potentially harmful interference with exploration and use of space" and has been interpreted as the Treaty's hook to orbital debris concerns. Article IX also could be linked to launch emissions and their potential for "harmful interference" with launch activities, but this would stretch Article IX beyond its original intent even farther than in the case of orbital debris. Rocket emissions from upper stages do add to the debris problem in low Earth orbit (mainly slag from SRMs), though this is a separate issue from stratospheric pollution.

The relatively unconstrained atmospheric flight operations enjoyed by space launch providers since the beginning of the space age cannot be taken for granted as a permanent condition. This status is, to some extent, the result of policy neglect from the scientific and regulatory communities. Research has been minimal and inconsistent. The hint of regulation due to ozone depletion is faint but always present. The launch industry has benefitted so far from this policy vacuum. Situations of this kind are inherently unstable and prone to sudden change in status, thus posing a risk to space launch. The next section discusses developments that might precipitate such a change.

Agents of Change

If the current laissez-faire regime is unlikely to persist, the launch community will be compelled to formulate a strategy to deal with the possibility of a sudden change in regulatory attention. If the space industry does carry out the various ambitious plans for new space vehicles, it must be prepared for the "tipping point"[25] wherein the scientific and regulatory communities (or perhaps environmental advocates) become aware that a large and growing launch industry has emerged.

It is impossible to predict how or when a tipping point may occur. In the meantime, it is prudent to develop an understanding of the context and implications of such an occurrence.

A. Perception

A change in regulatory attention inevitably follows from a change in perception. It is often the case that, with regard to public policy, perception equals reality. The overall perception of space launch emissions today is best described as a relic of the historical "inconsequential and static" view. This perception is increasingly out of balance with actual developments in the space industry.

In contrast to the "inconsequential and static" perception, the reality is one of global launch rate growth, introduction of new launch vehicles of all sizes, and the emergence of new launch sites (often referred to as "spaceports") across the globe. Space launch, as a result of public interest in its futuristic nature, generates attention when growth and new developments take place.

It is reasonable to expect that an adjustment in perception, possibly a paradigm shift, can occur as awareness increases.

It is often the case that a new perception can be, at least initially, out of proportion to the actual situation; the new perception "overshoots" reality.[23] This kind of tipping point for space launch would bring expanded, possibly undue, regulatory scrutiny to rocket emissions.

B. Entanglement with Climate Intervention

The atmospheric physics involved with the BC and alumina component of rocket emissions is directly related to the physics of attempts to mitigate climate change: so-called geoengineering or climate intervention. The goal of geoengineering is to add particles directly into the stratosphere in order to intercept a small portion of sunlight, preventing that energy from reaching the troposphere and so cooling the Earth's surface. As noted above, BC and alumina emitted by rocket engines likely cool the Earth's surface and so can be seen as a form of "weak" geoengineering. Indeed, BC and alumina have even been proposed in the scientific literature as geoengineering agents.[26]

The problem is that geoengineering is controversial and there is no formal policy regarding its deployment, of even in an experimental context. Policies and regulations to ban geoengineering have been proposed and the concept is widely condemned.[27] A global ban on "… injection of particles into the stratosphere…"[28] could present a problem for space launch, which currently injects approximately 10 gigagrams of BC and alumina particles into the stratosphere each year. Clearly, a ban on geoengineering would have to be formulated in a way that preserves the privilege of launch to emit potential geoengineering agents into the stratosphere. This would require strong policy engagement with the regulators which, in turn, requires that an understanding of rocket emissions with high scientific confidence be available.

Progress in geoengineering, whether initial experiments or preventative regulation, could present a Tipping Point for rocket exhaust.

C. New Propellants

The global launch industry has used four propellant combinations (LOX/kerosene, LOX/hydrogen, SRM, and hypergolic) at various levels since the start of the space age. New propellants are being proposed and it appears that LOX/methane powered launch vehicles will enter the global fleet soon,[6] possibly accounting for a significant portion of launches by 2030.

The level of understanding LOX/methane engine emissions is evolving; this propellant combination has never been the focus of models of ozone depletion or changes in atmospheric radiation. Methane fueled engines can be expected to emit, uniquely, potentially significant amounts of hydrogen oxides (HOx) into the stratosphere. Hybrid propellant rocket engines that may see use in space tourism[29] may result in significant nitrogen oxides (NOx) emissions. These could be important as HOx and NOx chemistry controls ozone concentrations in the stratosphere.

Geoengineering is controversial, and there is no formal policy regarding its deployment…

In many situations, change ignites interest in existing configurations. From a policy perspective, scientific interest in methane fueled rocket engines could lead to questions regarding existing propellants, for which the current level of understanding has few answers. This could be the tipping point for engagement from the regulatory community.

Preparedness: Filling the Blanks

Any of these potential tipping points could be the specific factor that brings awareness of a dynamic and growing launch industry to the regulatory community. If "small and inconsequential" becomes "large and problematic," the space launch community will need to be ready.

History informs us that the best course of action in anticipation of a realignment in perception is to acknowledge the change and gather an increased level of understanding before the arrival of the tipping point. As pointed out above, early spacefaring nations missed the opportunity to deal with space debris before it became a problem, in part due to gaps in knowledge. Today we have an opportunity to prevent the same thing from happening with rocket emissions by filling in the blanks in our scientific understanding.

Achieving an appropriate level of understanding of rocket emission effects on the global atmosphere requires collaboration across all stakeholders. The United States could take the lead by providing research funding and other incentives to its stakeholders and by inviting international participation in the research program. This should include agreement on the metrics regarding ozone depletion or radiative forcing that should be applied to launch vehicles.

The research community that would perform the laboratory, in situ, and modelling experiments could be initiated through the national network of federal laboratories, universities, and corporate resources that currently performs atmospheric research. This community already has the instrumentation, models, and research aircraft needed for the research program. Indeed, the same scientific infrastructure that has investigated aircraft emissions could be applied to the rocket emission problem with only modest modification.

A vigorous research program should incorporate global atmospheric models (e.g., for ozone loss, climate forcing, and pollutant interaction) and include the following components:

- Stratospheric plume measurements using in situ and remote sensing instruments
- Lab measurements to validate propellant-specific emissions and interactions
- Engine test stand measurements to determine bulk properties and measure exit plane exhaust composition
- Application of state of the art global chemistry and climate models using measured emissions and likely launch growth scenarios

International guidance for space debris mitigation provides a precedent for how emissions guidelines could evolve on the global stage. In the late 1990s, DoD and NASA devised the national debris mitigations guidelines, which were subsequently proposed to the international community. By 2007, a modified version of the guidelines was adopted by the U.N. Committee on the Peaceful Uses of Outer Space, and ultimately by the U.N. General Assembly. At the appropriate time, rocket emissions guidelines could undertake a similar process, backed up by high-confidence research. A proactive United States could be a primary driver of this activity as it was for debris mitigation. The alternative—waiting for others to take the initiative—may not yield satisfactory results for U.S. interests.

Conclusion

Rocket emissions inherently impact the stratosphere in a way that no other industrial activity does. This is a fundamental aspect of placing payloads into space using chemical propulsion. The different types of propulsion systems affect the stratosphere in different ways. This means that the various global launch organizations, national or commercial, have different impacts on the global atmosphere.

International concern for the global atmosphere is another fundamental fact. Many widely used industrial compounds have been eliminated by the most successful of the regulatory instruments, the Montreal Protocol, because they deplete ozone (e.g., CFCs) or they produce large climate forcing (e.g., HFCs). Rocket emissions, though they deplete ozone and cause climate forcing, so far have not been regulated due to the small number of launching states and annual Earth-to-orbit traffic consisting of about a hundred flights.

But there is little doubt that these two fundamental realities, rocket emissions impacts and international stewardship, could come into conflict, given a sufficiently vigorous launch industry. It cannot be predicted when this conflict will emerge, but the present day launch industry outlook suggests that it is on the horizon. At the same time, entanglement with future geoengineering regulation could affect space launch as well.

All of these potential future conflicts indicate that the launch community, in the U.S. and globally, should tackle the question of launch emissions while it is still manageable, and be prepared to respond to regulatory attention and inquiry. Experience with space debris mitigation strongly emphasizes this course of action: Act when concerns are small to prepare for a big future. In this case, that means initiating an aggressive scientific research program and being proactive in regulatory engagement.

References

[1] J.A. Vedda, Orbital Debris Remediation Through International Engagement, The Aerospace Corporation, March 2017 (http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2017/09/DebrisRemediation.pdf).

[2] M.N. Ross et al., 1997, Observation of Stratospheric Ozone depletion in Rocket Exhaust, *Nature*, 390, 62-64, 1997.

[3] S.O. Andersen and K, Sarma, 2002, *Protecting the Ozone Layer,* Earthscan Publications, Sterling VA.

[4] M. Ross and P. Sheaffer, 2014, Radiative forcing caused by rocket engine emissions. Earth's Future, 2: 177–196, doi:10.1002/2013EF000160.

[5] B. Kravits et al., 2012, Sensitivity of stratospheric geoengineering with black carbon to aerosol size and altitude of injection, *J. Geophys. Res.,* 117, D09203.

[6] Two large methane fueled engines are in final development: http://spacenews.com/musk-offers-more-technical-details-on-bfr-system/ and https://arstechnica.com/science/2017/10/blue-origin-has-successfully-tested-its-powerful-be-4-rocket-engine/.

[7] Scientific Assessment of Ozone Depletion: 2014, World Meteorological Association, Report No. 44.

[8] For example, Bank of America Merrill Lynch predicts the space industry will grow by a factor of eight by 2030; https://www.cnbc.com/2017/10/31/the-space-industry-will-be-worth-nearly-3-trillion-in-30-years-bank-of-america-predicts.html.

[9] M. Ross et al., 2009, Limits on the Space Launch Market Related to Stratospheric Ozone Depletion, *Astropolitics* Vol. 7.

[10] In 1990, M. Prather et al. (J, Geophys. Res., 95,18583-18590, 1990) published the first paper that identified rocket exhaust as a source of ozone depletion. A flurry of subsequent papers culminated as Chapter 10 in the *1991 Scientific Assessment of Ozone Depletion* (World Meteorological Association, Report No. 25).

[11] M. Ko et al., Better Protection of the Ozone Layer, *Nature*, 367, 1994; doi:10.1038/367505a0.

[12] Siskind, D. et al., 2013, Recent observations of high mass density polar mesospheric clouds: A link to space traffic?, http://onlinelibrary.wiley.com/doi/10.1002/grl.50540/abstract.

[13] Larson et al., Global atmospheric response to emissions from a proposed reusable space launch system, 2016, *Earth's Future,* 5, 37–48, doi:10.1002/2016EF000399.

[14] C. Jackman et al., A global modeling study of solid rocket *aluminum oxide* emission effects on stratospheric ozone, 1998, *Geophys. Res. Letts*., 25, 907-910.

[15] Ross, M, et al., 2010, Potential climate impact of black carbon emitted by rockets, *Geophys. Res, Letts.*, 37, doi:10.1029/2010GL044548; http://onlinelibrary.wiley.com/doi/10.1029/2010GL044548/pdf.

[16] https://www.esrl.noaa.gov/csd/assessments/ozone/2014/twentyquestions/Q20.pdf.

[17] https://www.epa.gov/climate-indicators/climate-change-indicators-climate-forcing.

[18] Advancing the Science of Climate Change, 2010, National Research Council, Chapter 26, https://www.nap.edu/read/12782/chapter/26.

[19] Description of NEPA history and process can be found at https://www.epa.gov/nepa

[20] onlinelibrary.wiley.com/doi/10.1029/97GL01560/abstract.

[21] The USAF, NASA, NOAA, and NCAR collaborated on the ACCENT program that sampled several rocket plumes; https://www.nap.edu/read/12782/chapter/26

[22] https://www.unenvironment.org/news-and-stories/press-release/montreal-protocol-marks-milestone-first-ratification-kigali.

[23] https://www.scientificamerican.com/article/wait-the-ozone-layer-is-still-declining1/; https://www.atmos-chem-phys.net/18/1379/2018/.

[24] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, January 27, 1967 (http://www.oosa.unvienna.org/oosa/en/SpaceLaw/outerspt.html).

[25] Gladwell, M., 2006, *The Tipping Point: How Little Things Can Make a Big Difference;* Little, Brown and Company; https://books.google.com/books?isbn=0759574731.

[26] For example: https://www.atmos-chem-phys.net/16/2843/2016/ and https://www.atmos-chem-phys.net/15/11835/2015/acp-15-11835-2015.pdf.

[27] https://www.wired.com/story/the-us-flirts-with-geoengineering/.

[28] This order of magnitude estimate follows from assuming 100 launches per year, each with 1 kiloton of propellant, an overall average 3% of combustion emission are alumina or BC particles, with 3 year stratospheric lifetime.

[29] http://www.virgingalactic.com/learn/.